

Precise photoproduction of the charged top-pions at the LHC with forward detector acceptances

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January 3, 2014

Abstract

We study the photoproduction of the charged top-pion predicted by the top triangle moose (*TTM*) model (a deconstructed version of the topcolor-assisted technicolor *TC2* model) via the processes $pp \rightarrow p\gamma p \rightarrow \pi_t^\pm t + X$ at the 14 *TeV* Large Hadron Collider (*LHC*) including next-to-leading order (*NLO*) *QCD* corrections. Our results show that the production cross sections and distributions are sensitive to the free parameters $\sin \omega$ and M_{π_t} . Typical *QCD* correction value is 7% \sim 11% and does not depend much on $\sin \omega$ as well as the forward detector acceptances.

PACS numbers: 12.60.Cn, 14.80.Cp, 12.38.Bx

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1 Introduction

The top quark is the heaviest known elementary particle which makes it an excellent candidate for new physics searches. Origin of its mass might be different from that of other quarks and leptons, a top quark condensate ($\langle t\bar{t} \rangle$), for example, could be responsible for at least part of the mechanism of electroweak symmetry breaking ($EW\!SB$). An interesting model involving a role for the top quark in dynamical $EW\!SB$ is known as the topcolor-assisted technicolor ($TC2$) model[1]. Higgsless models[2] have emerged as a novel way of understanding the mechanism of $EW\!SB$ without the presence of a scalar particle in the spectrum. Recently, combining Higgsless and topcolor mechanisms, a deconstructed Higgsless model was proposed, called the top triangle moose (TTM) model[3, 4]. In this model, $EW\!SB$ results largely from the Higgsless mechanism while the top quark mass is mainly generated by the topcolor mechanism. The TTM model alleviates the tension between obtaining the correct top quark mass and keeping $\Delta\rho$ small that exists in many Higgsless models, which can be seen as the deconstructed version of the $TC2$ model. The new physics models belonging to the topcolor scenario genetically have two sources of $EW\!SB$ and there are two sets of Goldstone bosons. One set is eaten by the electroweak (EW) gauge bosons W and Z to generate their masses, while the other set remains in the spectrum, which is called the top-pions (π_t^0 and π_t^\pm). Topcolor scenario also predicts the existence of the top-Higgs h_t^0 , which is the $t\bar{t}$ bound state. The possible signals of these new scalar particles have been extensively studied in the literature, however, most are done in the context of the $TC2$ model. Phenomenology analysis about the top-pions and top-Higgs predicted by the TTM model[3, 4, 5] is necessary.

The Large Hadron Collider (LHC) generates high energetic proton-proton (pp) collisions with a luminosity of $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$. It provides high statistics data at high energies. On the other hand hadronic interactions generally involve serious backgrounds which should be concerned. A new phenomenon called exclusive production was observed in the measurements of CDF collaboration include the exclusive lepton pairs production[6], photon photon production[7], dijet production[8], the exclusive charmonium (J/ψ) meson

photoproduction[9], etc. Complementary to pp interactions, studies of exclusive production of leptons, photon and heavy particles might be possible and opens new field of studying very high energy photon-photon ($\gamma\gamma$) and photon-proton (γp) interactions.

Following the experience from *HERA* and the *Tevatron* new detectors are proposed to be installed in the *LHC* tunnel as an additional upgrade of the *ATLAS* and *CMS* detectors. They have a program of forward physics with extra detectors located in a region nearly 100m-400m from the interaction point. These forward detector equipment allows one to detect intact scattered protons after the collision. Therefore the processes which spoil the proton structure, can be easily discerned from the exclusive photo-production processes. By use of forward detector equipment we can eliminate many serious backgrounds. This is one of the advantages of the exclusive photo-production processes.

A brief review of experimental prospects for studying high-energy $\gamma\gamma$ and γp interactions are discussed in Ref.[10] and cross sections are calculated for many *EW* and *BSM* processes. Many other phenomenological studies on photoproduction processes involve: supersymmetry[11, 12], extra dimensions[13, 14], unparticle physics[15], gauge boson self-interactions [16, 17, 18, 19, 20], neutrino electromagnetic properties[21, 22, 23], the top quark physics[24, 25], etc.

Photoproduction of the charged top-pion at leading order (*LO*) has been studied in Ref.[26] which proceeds via the subprocess $\gamma c \rightarrow \pi_t^\pm b$ mediated by the flavor changing couplings and through $\gamma b \rightarrow \pi_t^\pm t$ at the large hadron-electron collider (*LHeC*)[27]. At the *LHC*, in general pp collision, the charged top-pion can be produced in association with a top quark through bottom-gluon fusion, $gb \rightarrow t\pi_t^-$, and through gluon-gluon fusion, $gg \rightarrow \bar{b}t\pi_t^-$, phenomenologically similar to a charged Higgs boson in a two-Higgs-doublet model with low $\tan\beta$. Related *NLO* study can be find in Ref.[28]. On the other hand, $\pi_t^\pm t$ associated production at the γp collision *LHC* will be very clean or at least with backgrounds easy going, thus leading a good chance to be detected. It can be a complementary process to be studied in addition of $gb \rightarrow t\pi_t^-$. In this paper, we present this production at the γp collision assuming a typical *LHC* multipurpose forward detector. Accurate theoretical predictions including higher order *QCD* corrections are

included. Paper is organized as follows: in section 2 we present a brief introduction to the calculation framework including the *TTM* model description, *EPA* implementation and *LO* and *NLO* cross section calculations. Section 3 is arranged to present the numerical checks and results of our studies. Finally we summarize the conclusions in the last section.

2 Calculation Framework

2.1 The essential features of the *TTM* model

The detailed description of the *TTM* model can be found in Refs.[3, 4], and here we just briefly review its essential features, which are related to our calculation. The *EW* gauge structure of the *TTM* model is $SU(2)_0 \times SU(2)_1 \times U(1)_2$. The nonlinear sigma field Σ_{01} breaks the group $SU(2)_0 \times SU(2)_1$ down to $SU(2)$ and field Σ_{12} breaks $SU(2)_1 \times U(1)_2$ down to $U(1)$. To separate top quark mass generation from *EWSB*, a top-Higgs field Φ is introduced to the *TTM* model, which couples preferentially to the top quark. To ensure that most of *EWSB* comes from the Higgsless side, the *VEV*s of the fields Σ_{01} and Σ_{12} are chosen to be $\langle \Sigma_{01} \rangle = \langle \Sigma_{12} \rangle = F = \sqrt{2}\nu \cos \omega$, in which $\nu = 246 \text{ GeV}$ is the *EW* scale and ω is a new small parameter. The *VEV* of the top-Higgs field is $f = \langle \Phi \rangle = \nu \sin \omega$.

From above discussions, we can see that, for the *TTM* model, there are six scalar degrees of freedom on the Higgsless sector and four on the top-Higgs sector. Six of these Goldstone bosons are eaten to give masses to the gauge bosons W^\pm , Z , W'^\pm and Z' . Others remain as physical states in the spectrum, which are called the top-pions (π_t^\pm and π_t^0) and the top-Higgs h_t^0 . In this paper, we will focus our attention on photoproduction of the charged top-pions via γp collisions at the *LHC*. The couplings of the charged top-pions π_t^\pm to ordinary particles, which are related to our calculation, are given by Ref.[4]

$$\mathcal{L}_{\pi_t tb} = i\lambda_t \cos \omega \left\{ 1 - \frac{x^2[a^4 + (a^4 - 2a^2 + 2) \cos 2\omega]}{8(a^2 - 1)^2} \right\} \pi_t^+ \bar{t}_R b_L + h.c. \quad (1)$$

with

$$\lambda_t = \frac{\sqrt{2}m_t}{\nu \sin \omega} \left[\frac{M_D^2(\varepsilon_L^2 + 1) - m_t^2}{M_D^2 - m_t^2} \right], \quad a = \frac{\nu \sin \omega}{\sqrt{2}M_D}, \quad x = \sqrt{2}\varepsilon_L = \frac{2 \cos \omega M_W}{M_{W'}}. \quad (2)$$

Here we assume the CKM matrix to be identity and omit the light quark masses. M_D is the mass scale of the heavy fermion and $M_{W'}$ is the mass of the new gauge boson W' . Since the top quark mass depends very little on the right-handed delocalization parameter ε_{tR} , we have set $\varepsilon_{tR} = 0$ in Eq.(1). The parameter ε_L describes the degree of delocalization of the left-handed fermions and is flavor universal, the parameter x presents the ratio of gauge couplings. The relationship between ε_L and x , which is given in Eq.(2), is imposed by ideal delocalization.

Ref.[29] has shown that $M_{W'}$ should be larger than 380 GeV demanded by the $LEP II$ data and smaller than 1.2 TeV by the need to maintain perturbative unitarity in $W_L W_L$ scattering. It is obvious that the coupling $\pi_t t b$ is not very sensitive to the parameters $M_{W'}$ and M_D . Thus, the production cross sections of the subprocesses $\gamma b \rightarrow t \pi_t^-$ and $\gamma \bar{b} \rightarrow \bar{t} \pi_t^+$ are not strongly depend on the values of the mass parameters $M_{W'}$ and M_D . In our following numerical calculation, we will take the illustrative values $M_{W'} = 500 \text{ GeV}$ and $M_D = 400 \text{ GeV}$. In this case, there is $[M_D^2(\varepsilon_L^2 + 1) - m_t^2]/(M_D^2 - m_t^2) \approx 1$ and Eq.(1) can be approximately written as

$$\mathcal{L}_{\pi_t t b} \approx i \frac{\sqrt{2}m_t C}{\nu} \cot \omega \pi_t^+ \bar{t}_R b_L + h.c. \quad (3)$$

with

$$C = 1 - \frac{x^2[a^4 + (a^4 - 2a^2 + 2) \cos 2\omega]}{8(a^2 - 1)^2}. \quad (4)$$

It is obvious that constant C is not sensitive to the value of $\sin \omega$ and its value close to 1. The parameter $\sin \omega$ indicates the fraction of $EW SB$ provided by the top condensate. The top-pion mass M_{π_t} depends on the amount of top-quark mass arising from the the extended technicolor (ETC) sector and on the effects of EW gauge interactions[30], and thus its value is model-dependent. In the context of the TTM model, Ref.[4] has obtained the constraints on the top-pion mass via studying its effects on the relevant experimental observables. Similarly with Refs.[4, 31], we will assume it as a free parameter.

2.2 Equivalent Photon Approximation (EPA)

In γp collisions, the quasi-real photons are emitted from protons with very low virtuality so that it's a good approximation to assume that they are on-mass-shell. These quasi-real photons scattered with small angles and low transverse momentum. At the same time, protons emitting photons remain intact and are not spoilt. Intact protons thus deviate slightly from their trajectory along the beam path without being detected by central detectors. Deflected protons and their energy loss will be detected by the forward detectors with a very large pseudorapidity. Photons emitted with small angles by the protons show a spectrum of virtuality Q^2 and the energy E_γ . This is described by the equivalent photon approximation (EPA)[32] which differs from the point-like electron (positron) case by taking care of the electromagnetic form factors in the equivalent γ spectrum and effective γ luminosity:

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi} \frac{1}{E_\gamma Q^2} \left[\left(1 - \frac{E_\gamma}{E}\right) \left(1 - \frac{Q_{min}^2}{Q^2}\right) F_E + \frac{E_\gamma^2}{2E^2} F_M \right] \quad (5)$$

with

$$Q_{min}^2 = \frac{M_p^2 E_\gamma^2}{E(E - E_\gamma)}, \quad F_E = \frac{4M_p^2 G_E^2 + Q^2 G_M^2}{4M_p^2 + Q^2},$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1 + \frac{Q^2}{Q_0^2}\right)^{-4}, \quad F_M = G_M^2, \quad Q_0^2 = 0.71 \text{ GeV}^2,$$

where α is the fine-structure constant, E is the energy of the incoming proton beam which is related to the quasi-real photon energy by $E_\gamma = \xi E$ and M_p is the mass of the proton. $\xi = (|p| - |p'|)/|p|$, where p and p' are momentums of incoming protons and intact scattered protons, respectively. $\mu_p^2 = 7.78$ is the magnetic moment of the proton. F_E and F_M are functions of the electric and magnetic form factors. In this case, if both incoming emitted protons remain intact provides the $\gamma\gamma$ collision and it can be cleaner than the γp collision, however, γp collisions have higher energy and effective luminosity with respect to $\gamma\gamma$ interactions.

2.3 The cross sections up to NLO

We denote the parton level process as $\gamma(p_1)b(p_2) \rightarrow \pi_t^\pm(p_3)t(p_4)$ where p_i are the particle four momentums. The hadronic cross section at the LHC can be converted by integrating $\gamma b \rightarrow \pi_t^\pm t$ over the photon($dN(x, Q^2)$) and quark($G_{b/p}(x_2, \mu_f)$) spectra:

$$\sigma = \int_{\frac{M_{inv}}{\sqrt{s}}}^{\sqrt{\xi_{max}}} 2zdz \int_{Max(z^2, \xi_{min})}^{\xi_{max}} \frac{dx_1}{x_1} \int_{Q_{min}^2}^{Q_{max}^2} \frac{dN_\gamma(x_1)}{dx_1 dQ^2} G_{b/p}\left(\frac{z^2}{x_1}, \mu_f\right) \cdot \int \frac{1}{avgfac} \frac{|\mathcal{M}_n(\hat{s} = z^2 s)|^2}{2\hat{s}(2\pi)^{3n-4}} d\Phi_n, \quad (6)$$

where x_1 is the ratio between scattered quasi-real photons and incoming proton energy $x_1 = E_\gamma/E$ and x_2 is the momentum fraction of the protons momentum carried by the bottom quark. The quantity $\hat{s} = z^2 s$ is the effective *c.m.s.* energy with $z^2 = x_1 x_2$. M_{inv} is the total mass of the $\pi_t^\pm t$ final state. $\frac{2z}{x_1}$ is the Jacobian determinant when transform the differentials from $dx_1 dx_2$ into $dx_1 dz$. $G_{b/p}(x, \mu_f)$ represent the bottom quark parton density functions, μ_f is the factorization scale which can be chosen equal the renormalization scale μ_r when the loop calculation is included. $\frac{1}{avgfac}$ is the times of spin-average factor, color-average factor and identical particle factor. $|\mathcal{M}_n|^2$ presents the squared n-particle matrix element and divided by the flux factor $[2\hat{s}(2\pi)^{3n-4}]$. $d\Phi_n$ is the n-body phase space differential.

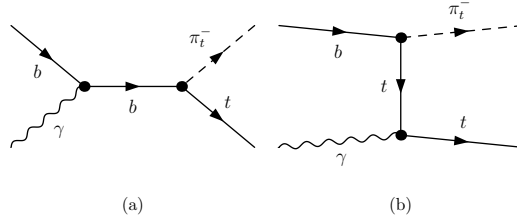


Figure 1: Tree parton level Feynman diagrams for $rb \rightarrow \pi_t^- t$ in the TTM frame.

The parton Feynman diagrams at tree level are shown in Fig.1(a,b). We only consider the $\pi_t^- t$ production while its charge-conjugate contribution is the same. At NLO QCD loop level, the Feynman diagrams are presented in Fig.2 and Fig.3, correspond to loop (σ^{loop}) and real (σ^{real}) contributions, respectively. There exist ultraviolet (UV) and soft/collinear IR singularities in σ^{loop} . To remove the UV divergences, we introduce the wave function renormalization constants $\delta Z_{\psi_{q,L,R}}$ for massless bottom and mas-

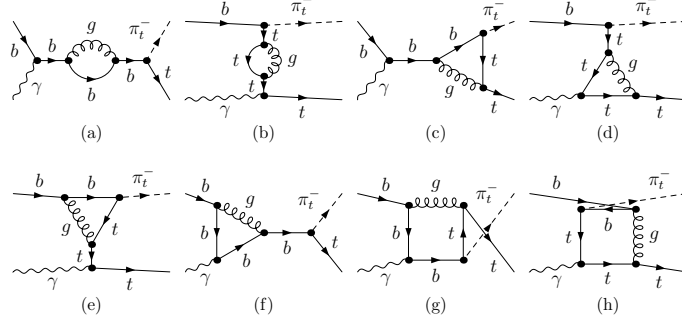


Figure 2: The QCD one-loop Feynman diagrams for the partonic process $\gamma b \rightarrow \pi_t^- t$ (a-h). Counterterm diagrams correspond to Fig.1 are not shown here.

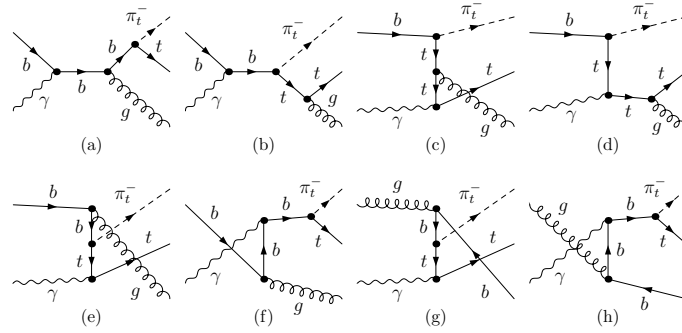


Figure 3: The tree level Feynman diagrams for the real gluon/light-(anti)quark emission subprocess $\gamma b \rightarrow \pi_t^- t g$ related to the first process in Eq.7(a-f) and $\gamma g \rightarrow \pi_t^- t \bar{b}$ related to the second process in Eq.7(g,h).

sive top fields as $\psi_{q,L,R}^0 = (1 + \delta Z_{\phi_{q,L,R}})^{\frac{1}{2}} \psi_{q,L,R}$. In the modified minimal subtraction (\overline{MS}) renormalization scheme the renormalization constants for the massless quarks, and massive top quark (defined on shell) are expressed as $\delta Z_{\psi_{q,L}} = -\frac{\alpha_s}{4\pi} C_F (\Delta_{UV} - \Delta_{IR})$, $\delta Z_{\psi_{q,R}} = -\frac{\alpha_s}{4\pi} C_F (\Delta_{UV} - \Delta_{IR})$ and $\frac{\delta m_t}{m_t} = -\frac{\alpha_s}{3\pi} [3\Delta_{UV} + 4]$, with $C_F = \frac{4}{3}$. $\Delta_{UV,IR} = \frac{1}{\epsilon_{UV,IR}} \Gamma(1 + \epsilon_{UV,IR}) (4\pi)^{\epsilon_{UV,IR}}$ refer to the UV and IR divergences, respectively. By adding renormalization part to the virtual corrections, any UV singularities are regulated leaving soft/collinear IR singularities untouched. These IR singularities will be removed by combine the real emission corrections. Singularities associated with initial state collinear gluon emission are absorbed into the definition of the parton distribution functions. We employ the \overline{MS} scheme for the parton distribution functions. Similar to the virtual part, we utilize dimensional regularization to control the singularities of the radiative corrections, which are organized using the two cutoff phase space slicing ($TCPSS$) method[33]. We adopt $TCPSS$ to isolate the IR singularities by introducing two cutoff parameters δ_s and δ_c . An arbitrary small δ_s separates the three-body final state phase space into two regions: the soft region ($E_5 \leq \delta_s \sqrt{\hat{s}}/2$) and the hard region ($E_5 > \delta_s \sqrt{\hat{s}}/2$). The δ_c separates hard region into the hard collinear (HC) region and hard noncollinear (\overline{HC}) region. The criterion for separating the HC region is described as follows: the region for real gluon/light-(anti)quark emission with \hat{s}_{15} (or \hat{s}_{25}) $< \delta_c \hat{s}$ (where $\hat{s}_{ij} = (p_i + p_j)^2$) is called the HC region. Otherwise it is called the \overline{HC} region where in our case related to

$$\begin{aligned} \gamma(p_1)b(p_2) &\rightarrow \pi_t^-(p_3)t(p_4)g(p_5) \\ \gamma(p_1)g(p_2) &\rightarrow \pi_t^-(p_3)t(p_4)\bar{b}(p_5) \end{aligned} \tag{7}$$

correspond to real gluon emission and real light-(anti)quark emission partonic processes, respectively. After combining all these contributions above, the UV and IR singularities in $\sigma^{total} = \sigma^{born} + \sigma^{loop} + \sigma^S + \sigma^{HC} + \sigma^{\overline{HC}}$ are exactly canceled. Dependence on the arbitrary small cutoff parameters δ_s and δ_c are then vanished. These cancelations can be verified numerically in our numerical calculations.

3 Numerical Results and Discussions

We use FeynArts, FormCalc and our modified LoopTools (FFL)[34, 35, 36] packages to perform the numerical calculation. We use CT10[37] for the parton distributions for collider physics and BASES[38] to do the phase space integration. In the numerical calculations, we take the input as $M_p = 0.938272046$ GeV, $M_Z = 91.1876$ GeV, $M_W = 80.385$ GeV, $M_t = 173.5$ GeV, $\alpha(M_Z^2)^{-1} = 127.918$ [39], $\sqrt{s} = 14$ TeV. For the strong coupling constant $\alpha_s(\mu)$, we use the two-loop evolution of it with the QCD parameter $\Lambda^{n_f=5} = 226$ MeV and get $\alpha_s(\mu_0) = 0.113$. N_f is the number of the active flavors. We choose two sets of the parameters related to TTM model:

- Scenario 1: $M_D = 400$ GeV, $\sin \omega = 0.5$, $M_{W'} = 500$ GeV, $M_{\pi_t} = 400$ GeV
- Scenario 2: $M_D = 400$ GeV, $\sin \omega = 0.2$, $M_{W'} = 500$ GeV, $M_{\pi_t} = 200$ GeV

correspond to high (low) M_{π_t} regions, respectively. The detected acceptances are chosen to be[17, 18, 40]:

- ξ_1 : $CMS - TOTEM$ forward detectors with $0.0015 < \xi < 0.5$
- ξ_2 : $CMS - TOTEM$ forward detectors with $0.1 < \xi < 0.5$
- ξ_3 : $AFP - CMS$ forward detectors with $0.0015 < \xi < 0.15$.

Before presenting the numerical predictions, several checks should be done. First, The UV and IR safeties are verified numerically after combining all the contributions at the QCD one loop level. We display random phase space points as well as the cancelation for different divergent parameters with the help of OneLoop[41] to compare with our modified LoopTools. Second, when do the phase space integration, we use Kaleu[42] to cross check especially for the hard emission contributions. Third, since the total cross section is independent of the soft cutoff $\delta_s (= \Delta E_g/E_b, E_b = \sqrt{\hat{s}}/2)$ and the collinear cutoff δ_c , trivial efforts should be done to check such independence. Fourth, the scale (μ) dependence should be reduced after considering the NLO corrections. Indeed, our results

show that the scale uncertainty can be reduced obviously. Choose the input scenario 1 as an example, if μ varies from $1/8\mu_0$ to $\mu_0 = M_t$, the LO cross section varies from 3.2 fb to 6 fb while NLO predictions stay much flat between 5.5 fb to 6.4 fb . For more details, see Fig.4, where we show the scale (μ) dependence of the LO and NLO QCD loop corrected cross sections for $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$. In the further numerical calculations, we fix $\delta_s = 10^{-4}$, $\delta_c = \delta_s/50$ and choose $\mu = \mu_0 = M_t$.

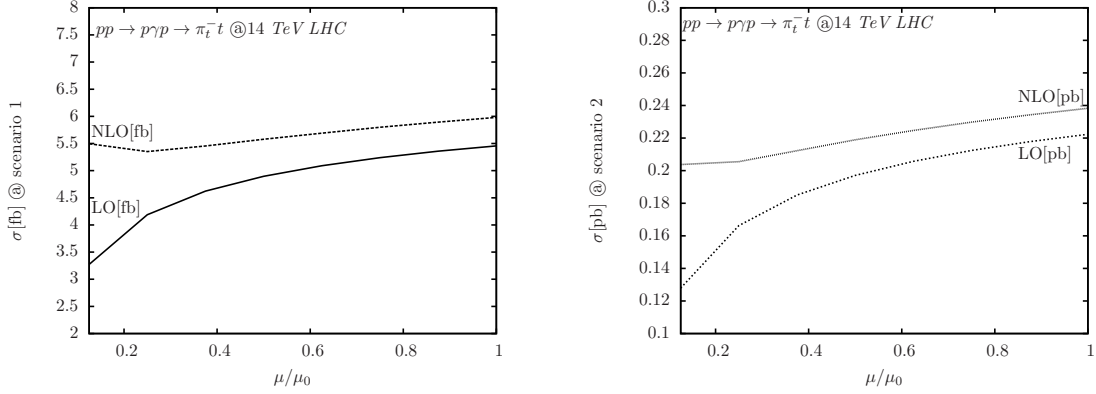


Figure 4: The scale(μ) dependence of the LO and NLO QCD corrected cross sections for $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$ at the $\sqrt{s} = 14$ TeV LHC with $\mu_0 = M_t$, $\delta_s = 10^{-4}$ and $\delta_c = \delta_s/50$. The experimental detector acceptances ($\xi_{min} < \xi < \xi_{max}$) are supposed to be $0 < \xi < 1$. Solid and dashed lines for Scenario 1, LO and NLO , respectively, while dotted and dot-dotted lines for Scenario 2, LO and NLO , respectively.

3.1 Cross sections and Distributions

In Fig.5 we present the cross sections (the left panel) for NLO predictions and K-factor (the right panel) defined as σ^{NLO}/σ^{LO} for $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$ as functions of different values of input parameters in the TTM model. One is $\sin \omega$ and the other is the top-pion mass M_{π_t} . Here we choose the detector acceptance as $0.0015 < \xi < 0.5$. The other parameters related to the TTM model are chosen to be $M_D = 400$ GeV and $M_{W'} = 500$, with $\sin \omega$ varies from 0.2 to 0.8 and M_{π_t} from 200 to 400 GeV , respectively. Our results show that the total LO and NLO cross sections are sensitive to the input parameter $\sin \omega$.

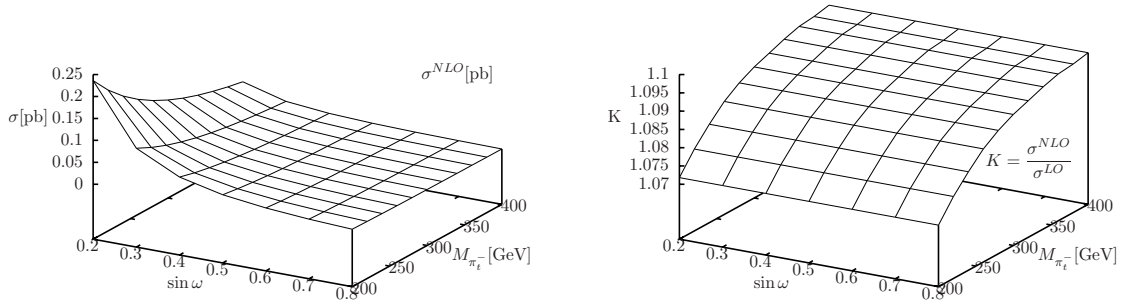


Figure 5: Cross sections (the left panel) for NLO predictions and K-factor (the right panel) defined as σ^{NLO}/σ^{LO} for $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$ as functions of different values of parameters in TTM models at 14 TeV LHC . Here we choose $0.0015 < \xi < 0.5$. The other parameters related to TTM models are chosen to be $M_D = 400$ GeV , $M_{W'} = 500$, with $\sin \omega$ varies from 0.2 to 0.8 and $M_{\pi_t^-}$ from 200 to 400 GeV , respectively, and the other TTM model input parameters are chosen to be scenario 2.

When $\sin \omega$ becomes larger, the cross sections reduce obviously. Same behavior can be found for the charged top-pion mass $M_{\pi_t^-}$. When the mass becomes heavier, the phase space of final states are suppressed thus leading lower cross sections. The right panel presents the K-factor dependence on $\sin \omega$ and $M_{\pi_t^-}$. No matter how $\sin \omega$ changes, the K-factor does not change much with a fixed top-pion mass. While for $M_{\pi_t^-}$ become larger from 200 to 400 GeV , the K-factor grows up step-by-step, however, not very much, see, from 1.07 to 1.1, leading the NLO QCD corrections up to around 7% \sim 11% within our chosen parameters.

To see how the cross sections depend on the detector acceptances, in Fig.6 we fix $\xi_{min} = 0.0015$ and take ξ_{max} as a running parameter. One should note here that the detector acceptance is indeed a step function of ξ while here we show the dependence on ξ qualitatively. Cross sections for the two input scenarios are presented as ξ_{max} running from 0.15 to 1. Left panel present results for scenario 1 with dotted and dot-dotted lines for LO and NLO , while right panel for scenario 2 with solid and dashed lines for

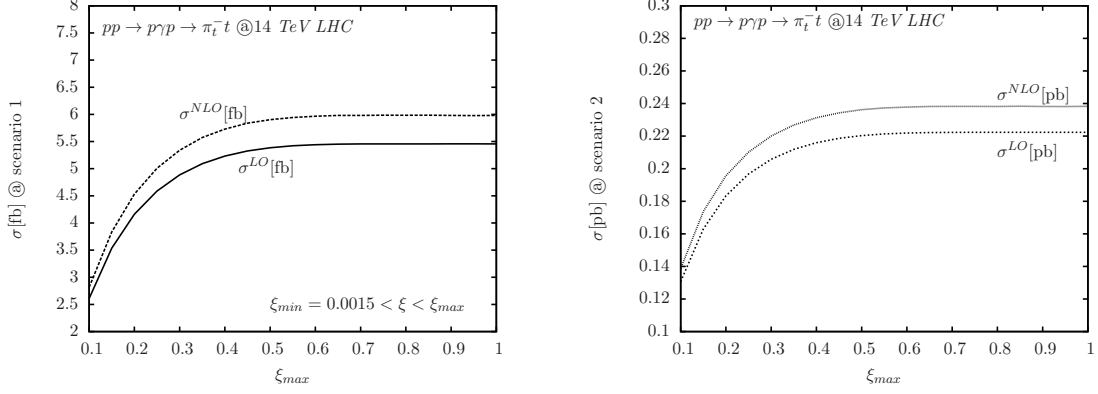


Figure 6: Cross sections for LO and NLO predictions for $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$ as functions of different values of ξ_{max} detector acceptances at the 14 TeV LHC . Here we fix $\xi_{min} = 0.0015$ and take ξ_{max} as a running parameter from 0.15 to 1. Left panel with units in fb for TTM scenario 1 with solid and dashed lines for LO and NLO predictions, while right axis in pb for TTM scenario 2 with dotted and dot-dotted lines for LO and NLO , respectively.

LO and NLO predictions, respectively. From these panels, we can see for $\xi_{max} < 0.5$, the cross section enhance rapid when ξ acceptances become larger. Case is different for $\xi_{max} > 0.5$ where little contributions contribute. Furthermore, no matter how the detector acceptances changes, the ratio of σ^{NLO} to σ^{LO} does not change much. A typical value of K-factor equal 1.09 for scenario 1 and 1.07 for scenario 2, lead the NLO QCD loop corrections up to 9% and 7% and keep unchange as functions of running ξ .

We present the transverse momentum (p_T) and rapidity (y) distributions for the charged top-pion in Fig.7. For $p_T^{\pi_t^-}$, NLO predictions can enhance the LO distributions obviously around the peak range and the same behavior can be found for the p_T^t distributions. It will be interesting to see $y^{\pi_t^-}$ where the NLO corrections can shift the LO rapidity obviously in the way of moving the position where $y^{\pi_t^-}$ peaked. Take $0.0015 < \xi < 0.5$ as an example, the distribution $y^{\pi_t^-}$ peaked at $y=-0.18$ for LO while the NLO predictions move the LO $y^{\pi_t^-}$ peak to $y=-0.42$ but no obvious enhancement to the LO predictions.

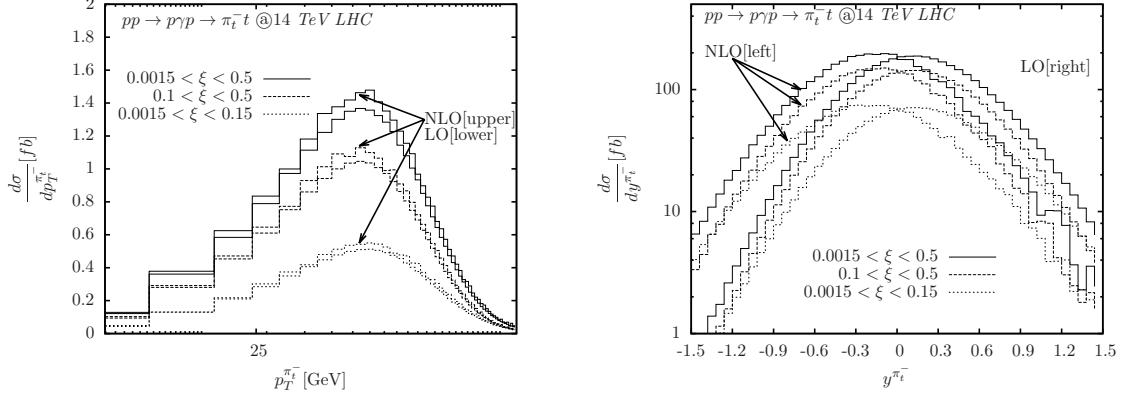


Figure 7: The LO (lower curves) and NLO (upper curves) transverse momentum (p_T) and Rapidity (y) distributions of the charged top-pion π_t^- for the process $pp \rightarrow p\gamma p \rightarrow \pi_t^- t + X$ at the 14 TeV LHC . The experimental detector acceptances ($\xi_{min} < \xi < \xi_{max}$) are chosen to be $0.0015 < \xi < 0.5$ (solid lines), $0.1 < \xi < 0.5$ (dashed lines) and $0.0015 < \xi < 0.15$ (dotted lines), respectively, and the TTM model input parameters are chosen to be scenario 2.

3.2 Signal Background Analysis and Parameter Sensitivity

Now let's turn to the signal and background analysis. From Ref.[4] we see that, for $M_{h_t} \geq 300 GeV$ and $M_{\pi_t} \leq 600 GeV$, the charged top-pions π_t^- dominantly decay into $\bar{t}b$ and there is $Br(\pi_t^- \rightarrow \bar{t}b) > 90\%$. As for the mass of M_{π_t} become heavier, the validity of this statement is no longer independent of the mass of, for example, top-Higgs mass M_{h_t} . However, for each value of $\sin \omega$, a specific range of masses for the top-Higgs is excluded by the Tevatron data. For example, the illustrative value $\sin \omega = 0.5$, the data implies that the mass range $140 GeV < M_{h_t} < 195 GeV$ is excluded. Here we concentrate on the case where $M_{h_t} \geq 350 GeV$. Even though, as the mass M_{π_t} become heavier than $600 GeV$, the decay mode $\pi_t^\pm \rightarrow W^\pm H_t$ becomes more and more competitive, where the assumption of a branching ratio $Br(\pi_t^- \rightarrow \bar{t}b) < 90\%$ should be considered. We concentrate on the $\pi_t^\pm \rightarrow \bar{t}b(t\bar{b})$ decay modes. In this case, photoproduction of the charged top-pion associated with a top quark can easily transfer to the $t\bar{t}b$ final state through

$$pp \rightarrow p\gamma p \rightarrow \pi_t^- t \rightarrow \bar{t}bW^+b \rightarrow W^- \bar{b}bW^+b \rightarrow \ell^+ \ell^- \bar{b}bb \cancel{E}_T \quad (8)$$

thus gives rise to the $\ell^+\ell^-\bar{b}b\cancel{E}_T$ signature via γb collisions at the *LHC*.

The backgrounds appear in two kind of processes. The first, called irreducible background comes from photoproduction with very similar final state as the signal. The second has the same final state but occurs through different processes induced by partonic interactions and is called reducible background. The key difference between photoproduction and partonic interactions at the *LHC* lies in the absence of colour exchange on the photon side. This causes an important zone of rapidity to be completely devoid of hadronic activity called a large rapidity gap(*LRG*) and which is natural way to distinguish photoproduction and partonic backgrounds. In the framework of EPA, emitted quasi-real photons from the protons have a low virtuality and scattered with small angles from the beam pipe. Therefore when a proton emits a quasi-real photon it should also be scattered with a small angle. Hence, intact scattered protons exit the central detector without being detected. This causes a decrease in the energy deposit in the corresponding forward region compared to the case in which the proton remnants are detected by the calorimeters. Consequently, for any reaction like $pp \rightarrow p\gamma p \rightarrow pX$, one of the forward regions of the central detector has a significant lack of energy. The region with a lack of energy (or equivalently lack of particles) defines a forward *LRG*. Backgrounds from usual pp deep inelastic processes can be rejected by applying a selection cut on this quantity.

In addition, another tagging method based on the same physics properties of photoproduction events is to place an exclusivity condition on reconstructed particle tracks on the gap side which can obviously reduce partonic backgrounds[43]. Even if both conditions are used and partonic background is reduced to a level that not allows proper signal extraction, elastic photon emission can be tagged using very forward detector (*VFD*)[44] placed hundreds of meters away from the interaction point. For instance, the case for which *VFD* stations would be put at 220m and 420m from the interaction point and is mandatory in order to retain partonic backgrounds low[45]. Indeed, when an intact proton is scattered with a large pseudorapidity it escapes detection from the central detectors. But since its energy is lower than the beam energy, its trajectory decouples from the beam path into the very forward region. Forward detectors can detect particles with a

large pseudorapidity. The detection of final state intact protons by the forward detectors provides a characteristic signature. Backgrounds from usual *DIS* processes can also be rejected by use of this characteristic signature provided by the forward detectors.

Therefore in our paper, the only considered backgrounds come from protoproduction. From this point we can see that the backgrounds would come from $t\bar{t}$ plus *jet* ($t\bar{t}j$) photoproduction. Different from normal pp collision, in γp collisions where photoproduction of top quark pairs has similar cross sections like, for example, W^-t productions, only ~ 1.4 pb[10], while for $t\bar{t}j$, roughly ~ 16 fb after considering the fake b-tagging efficiency, leading such related background processes easier going than in case of the pp collision. Here we assume that the π_t^\pm fully decay to $t\bar{b}(\bar{t}b)$ if $M_{\pi_t} < 600\text{GeV}$ while $Br(\pi_t^\pm \rightarrow t\bar{b}(\bar{t}b)) < 90\%$ [4] should be considered if $M_{\pi_t} \geq 600\text{GeV}$. For the *SM* gauge bosons W^\pm decay leptonically, $W^\pm \rightarrow l\nu$, the signal is $S = \mathcal{L} \times \sigma(pp \rightarrow prp \rightarrow \pi_t^\pm t \rightarrow t\bar{t}b) \times K^{NLO} \times [BR(t \rightarrow Wb)]^2 \times [3 \times BR(W \rightarrow l\nu)]^2$ and the corresponding background as $B = \mathcal{L} \times \sigma(pp \rightarrow prp \rightarrow t\bar{t}j) \times Eff_j \times [BR(t \rightarrow Wb)]^2 \times [3 \times BR(W \rightarrow l\nu)]^2$ with $j = u, d, c, s, b, \bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{b}, g$ and Eff_j is the fake b-tagging efficiency of the jets. For c-jets and light jets, a fake b-tagging efficiency of 10% and 1% respectively is assumed. Here we take $BR(t \rightarrow Wb) \approx 1$ and $BR(W \rightarrow l\nu) \approx 0.108$. For the luminosity \mathcal{L} we take $1fb^{-1}$, $10fb^{-1}$, $100fb^{-1}$, respectively. In Table.1, we present the parameters sensitivity on the signal background ratio S/\sqrt{B} . Here we choose $0.0015 < \xi < 0.5$. The background cross section after consider all the b-tagging efficiency and the rejection factors for the c, \bar{c} and light jets is $1.68 fb^{-1}$. The 5σ and 3σ bounds of the parameters are presented with three values of the luminosity. For $S/\sqrt{B} > 5$, the new physics signal will be detected obviously while for $S/\sqrt{B} < 3$ it will be challenge to be detected.

Our results show that, for low M_{π_t} , the $\sin\omega$ discovery range is larger than the case of high M_{π_t} . As the top-pion mass becomes larger, the $\sin\omega$ discovery range is suppressed. When $M_{\pi_t} > 900\text{GeV}$, heavy final state strongly suppress the phase space. The signal becomes much small and makes it more challenge to be detected. In this case, higher luminosity is needed to make the detection possible and push the discovery boundary larger. Two ways can be used in order to constraint the parameters or the excluding

M_{π_t} [GeV]	$\sin \omega$					
	$\mathcal{L} = 1fb^{-1}$		$\mathcal{L} = 10fb^{-1}$		$\mathcal{L} = 100fb^{-1}$	
	5σ	3σ	5σ	3σ	5σ	3σ
300	0.596	0.694	0.800	0.867	0.923	0.950
400	0.450	0.546	0.671	0.762	0.851	0.902
500	0.340	0.423	0.543	0.642	0.758	0.833
600	0.258	0.327	0.431	0.526	0.650	0.743
700	0.183	0.231	0.308	0.386	0.500	0.599
800	0.137	0.172	0.232	0.292	0.388	0.478
900	< 0.1	0.131	0.174	0.220	0.294	0.370
1000	< 0.1	< 0.1	0.132	0.164	0.223	0.282
1100	< 0.1	< 0.1	< 0.1	0.123	0.165	0.208
1200	< 0.1	< 0.1	< 0.1	< 0.1	0.122	0.149

Table 1: The TTM parameters $\sin \omega$ and M_{π_t} sensitivities on the signal background ratio S/\sqrt{B} . 5σ for the discovery boundary and 3σ for the excluding boundary. The detector acceptance here is chosen to be $0.0015 < \xi < 0.5$.

boundary more strictly: one is, as we see, to enhance the luminosity which can expand the related parameter space, see in Table.1, while the other one is to take more kinematical cuts to improve the ratio S/\sqrt{B} . In our case for example, if a p_T^{jet} cut taken to be larger than 200 GeV can strongly suppress the ttj backgrounds and thus lead better S/\sqrt{B} in parts of the TTM parameter space.

4 Summary

In this work, we present the precise photoproduced charged top-pion π_t^\pm production associated with a top through $pp \rightarrow p\gamma p \rightarrow \pi_t^\pm t + X$ at the 14 TeV LHC at NLO QCD loop level. We find the cross sections are sensitive to TTM parameters, and the smaller

the $\sin\omega$ is or the lighter the top-pion π_t^- is, the larger the cross sections will be. The typical QCD correction value is $7\% \sim 11\%$ which does not depend much on the TTM parameter $\sin\omega$ as well as the detector acceptances ξ . We also present the 5σ discovery and 3σ excluding boundaries as functions of the TTM parameters for three values of the luminosity at the future LHC .

Acknowledgments

Sun Hao thanks Dr. Inanc Sahin for his kindness to provide invaluable advice. Project supported by the National Natural Science Foundation of China (No. 11205070, 11275088), Shandong Province Natural Science Foundation (No. ZR2012AQ017), Natural Science Foundation of the Liaoning Scientific Committee (No. 201102114), Foundation of Liaoning Educational Committee (No. LT2011015) and by the Fundamental Research Funds for the Central Universities (No. DUT13RC(3)30).

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